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Application of Laser-Two-Focus Velocimetry to Transonic Turbine Flows

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Abstract

At DLR-Göttingen the Laser-Two-Focus Technique (L2F) is routinely applied to acquire flow field information for cascade and turbomachine flows. An update of the electronic part of the system led to performance improvements with respect to the speed of the measurements and the quality of the results. When investigating rotor flows the spatial resolution could be improved by dividing the blade pitch into 32 segments. At each angle the velocity distribution is stored which allows the evaluation of the Reynolds' stress. Additional to velocities and turbulence quantities also the concentration of particles is measured thus enabling the investigation of coolant flow concentrations etc. The general features of the L2F system will be discussed especially in terms of data rate. A description of the newly written evaluation program will be given which pays special attention to measurements in a rotor.

1. Introduction

Flows in turbomachines display some annoying features as high spatial and temporal inhomogeneity and lack of accessibility which make it difficult to gain information on such flows. In the last two decades optical techniques, especially Laser anemometry have been increasingly applied to turbomachinery flows. Whereas Laser Doppler Anemometry (LDA) is superior in flows with good accessibility and moderate spatial gradients and in flows with very high turbulence the Laser-2-Focus (L2F) (sometimes also called Laser Transit) - technique is especially useful in measuring flow velocities and turbulence quantities in narrow blade channels or in high speed applications.

2. General features of the L2F system

The measurement principle of L2F, depicted in Figure 1, is rather simple. The L2F-measuring device generates two highly focussed light beams in the probe volume which act as a 'light gate' for tiny particles in the flow. The scattered light from the particles provides two successive pulses and from the time interval between the pulses the velocity perpendicular to the Laser beams can be derived. A detailed description may be found in [1], [2] or [3].

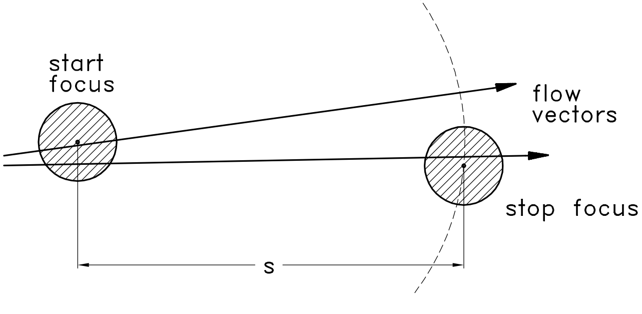

Figure 1: The L2F measurement volume

The fact that the measurement volume consists of two small focuses determines the general features of the L2F system: The light intensity in a focus is much higher than in a Laser Doppler (LDA) measurement volume, so very small particles are detected. But the second (stop) focus has to be rotated around the start focus into the direction of the mean flow, to enable the particles to pass both focuses. Even if the two focuses are perfectly aligned to the mean flow direction the probability of a successful measurement event will decrease with increasing level of the transverse turbulence, Tu_V. This is shown in Figure 2, where the probability of a particle to traverse both focuses is plotted as a function of the similarity parameter $\mathrm{Tu}_\mathrm{V} * s/d$.

If the two focuses are perfectly aligned to the mean flow direction the probability of a particle to traverse both focuses was computed with the assumptions that the L2F angle distribution is near a Gaussian shape and that the focuses can be approximated as cylinders of fixed diameter d. The following equations could be derived (N = number of particles traversing the start focus, see also nomenclature in the appendix; details of the computation in [4]):

$$P_{\mathrm{succ;0}} = \frac{n_0}{N} = \begin{cases} \dfrac{d}{s \cdot Tu_\mathrm{V} \cdot \sqrt{2\pi}} \left[1 - \dfrac{17}{216}\left(\dfrac{d}{s \cdot Tu_\mathrm{V}}\right)^2\right] & \text{if } \dfrac{d}{s} \leq Tu_\mathrm{V} \\ 1 - 0.902\dfrac{s \cdot Tu_\mathrm{V}}{d} + 0.2698\left(\dfrac{s \cdot Tu_\mathrm{V}}{d}\right)^2 & \text{if } \dfrac{d}{s} \geq Tu_\mathrm{V} \end{cases} \tag{1}$$

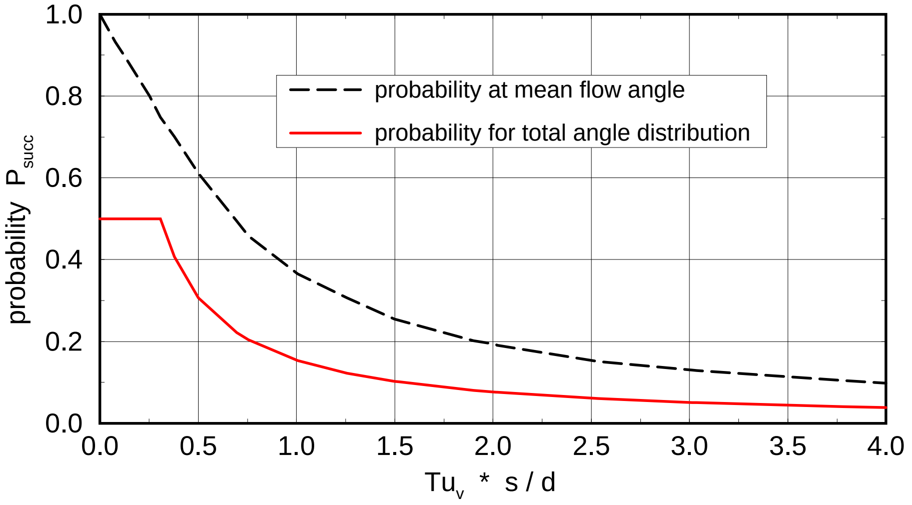

Figure 2: Probability of a particle to traverse both L2F-focuses

If the L2F measurement is performed at a sufficient number of equally spaced angle settings, in order to scan the full flow angle distribution, the probability of successfully hitting both focuses may be expressed as following equation, valid for all types of flow angle distributions and turbulence intensities [4]:

$$P_{\mathrm{succ;total}} = \sum_{\mathrm{i=1}}^{\mathrm{m}} \frac{n_\mathrm{i}}{N \cdot m} = \frac{m-1}{m} \cdot \frac{d}{s} \cdot \frac{1}{|\alpha_\mathrm{m} - \alpha_1|} \quad \text{(m = number of L2F angle settings)} \tag{2}$$

In case of an angle distribution with Gaussian shape the minimum angle range $|\alpha_\mathrm{m} - \alpha_1|$ is estimated to be either $k \cdot Tu_\mathrm{V}, (k \approx 6\ldots7)$, if $\mathrm{Tu}_\mathrm{V} > \frac{\mathrm{2d}}{\mathrm{ks}}$ or $2d/s$, if Tu_V is smaller. Therefore following formula may be derived from equation (2). The probabilities resulting from the following formula (taking k = 6.5) are displayed in Figure 2, too.

$$P_{\mathrm{succ;total}} = \sum_{\mathrm{i=1}}^{\mathrm{m}} \frac{n_\mathrm{i}}{N \cdot m} \approx \frac{d}{s} \cdot \frac{1}{k \cdot Tu_\mathrm{V}}, \text{ if } Tu_\mathrm{V} > \frac{2d}{ks} \quad \text{resp.} \approx \frac{1}{2}, \text{ if } Tu_\mathrm{V} \text{ is smaller} \tag{3}$$

Equation (3) is normally too optimistic, as it does not take into account that during measurements in a rotor the L2F angle settings have to include the full flow angle range of the whole blade gap, and as it supposes an a priori knowledge of the flow angle range, but equation (2) is valid for such cases, too. From the above equations it is clear that at elevated turbulence intensities the L2F system gives a much lower data rate than LDA. But the L2F system is superior in detecting small submicron particles which have to be used in flows with large gradients of velocity and the small L2F measurement volumes enable measurements close to walls – both features are especially useful in high speed turbomachine flow investigations.

3. The L2F system of the DLR Göttingen

The two focuses of our L2F device have diameters of 8 μm and their separation, s, is 207 μm. Our system only measures 2D-vectors of the fluid velocity. An advantage of the 2D-system is the slender light cone of 7.2° enclosed angle which provides excellent access to narrow blade channels. The particles used in our tunnel are produced from an oil-solvent mixture and have diameters $< 0.3\mu m$.

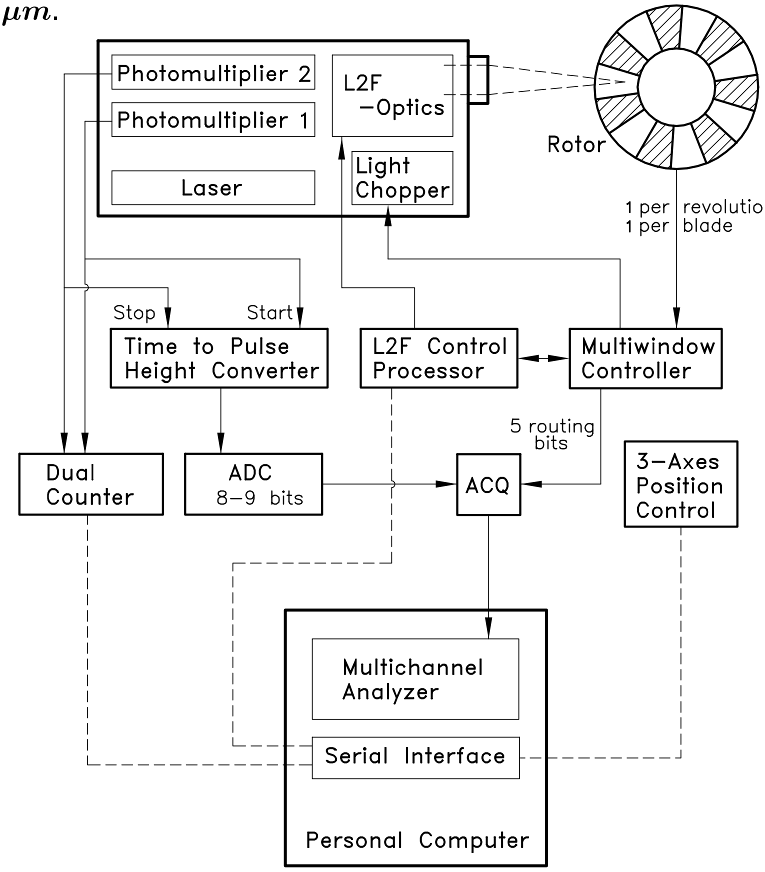

Figure 3: The L2F system of DLR Göttingen

In Figure 3 the system layout is shown. The optical parts are all assembled in a rigid casing, called optical head. It contains the laser, the photomultipliers to detect the scattered light, the optical parts to produce the two focuses and to transmit them to the measurement location, and finally a Bragg cell which serves as a light chopper in the case of measurements inside rotating blade channels. Such a light chopper is necessary to protect the multipliers from the intense reflected light which is produced when the metal blade hits the measurement volume.

A scattered light pulse from the start focus photomultiplier followed by a scattered light pulse from the stop focus photomultiplier triggers a fast measurement cycle: the transit time is converted into a 8 to 12 bit number (8 or 9 bits are sufficient for all our investigations as a number of transit time ranges can be chosen), the 'Multiwindow Controller' delivers the actual circumferential position in the rotor with a precision of 1/32 of the blade gap. The 8 or 9 bits from the ADC and the 5 bits from the Multiwindow Controller are tagged together to a 'data word' by a simple electronic device (here called ’ACQ’). Then the data word is stored in the ’Multichannel Analyzer’, a board installed in and controlled by a personal computer (PC).

The whole measurement procedure is PC-controlled, automatically changing the L2F angle, measuring the velocity distribution at the specific angle and storing the distribution for each angle. In contrast to the measurements described in [3] not only the integrated distributions were stored.

The storage of the fully two-dimensional velocity distribution instead of only the two marginal distributions of transit time and angle led to several improvements of which the most important are:

- Not only mean flow vectors and turbulence intensities can be obtained, but also Reynolds shear stress.
- The evaluated data are more accurate, mainly due to the fact that the background noise in the distributions of particle transit times coming from uncorrelated events (e.g. stray light from walls) can be subtracted at every measured angle.
- The measurement procedure can be organized more flexibly, e.g. if the angle setting of the measurement procedure is missing a part of the flow angle range, some measurements at other L2F-angles may be added easily.

A statistical evaluation procedure is necessary to extract the desired mean flow values from the stored transit time distributions at the used angle settings. The evaluation procedure is described in the Appendix.

The personal computer of the system also controls a dual counter which counts the total number of particles passing start and stop focus and the 3-axes position control which is used to move the measurement volume in axial and radial direction. Some more details about the L2F system of the DLR-Göttingen may be found in [5].

4. Measurement results

Some examples from recent measurements in transonic flows will be shown, where the above mentionned improvements played an important role, especially results from L2F measurements at a turbine rotor, where flow field measurements at different stations in front, inside and downstream of the rotor and at different rotor speeds have been conducted.

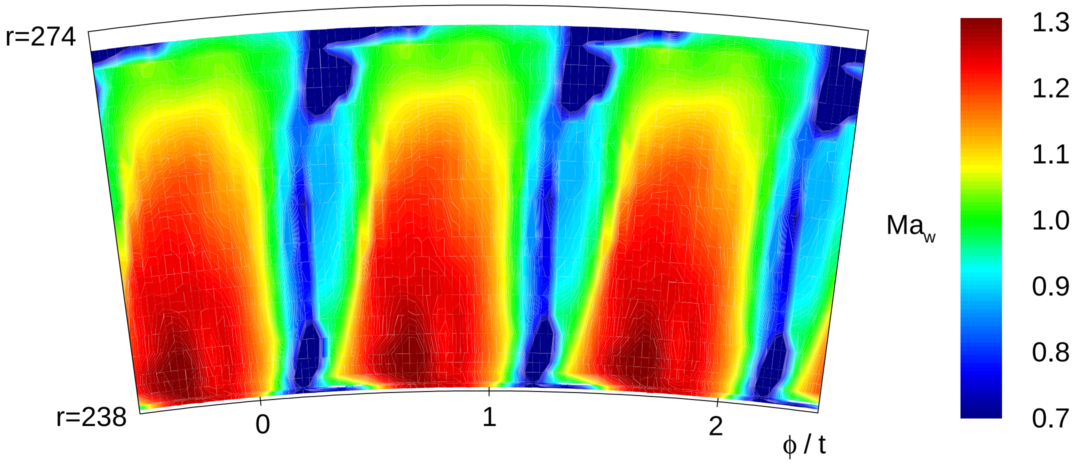

Figure 4: Mach number in the rotating relative system from L2F measurements downstream of a rotor

As the L2F velocimeter enables measurements close to walls, investigations of the flow field at different radii from 1 % blade height (equivalent to 0.4 mm from the hub) to 95 % blade height have been performed. At this x-position the measurement was not extended nearer to the casing as the plane window introduced a certain disturbance of the flow near the casing. Figure 4 shows the result of such a measurement 3 mm downstream of the rotor exit. Wakes and secondary flow near hub and casing can be clearly seen.

In Figure 5 the streamwise turbulence intensity in the mid section is presented. The turbulence intensity field exhibits elevated values not only in the wake but also at the location of the shock at the trailing edge, because such a shock is always slightly unstable, giving rise to an apparent elevated turbulence level.

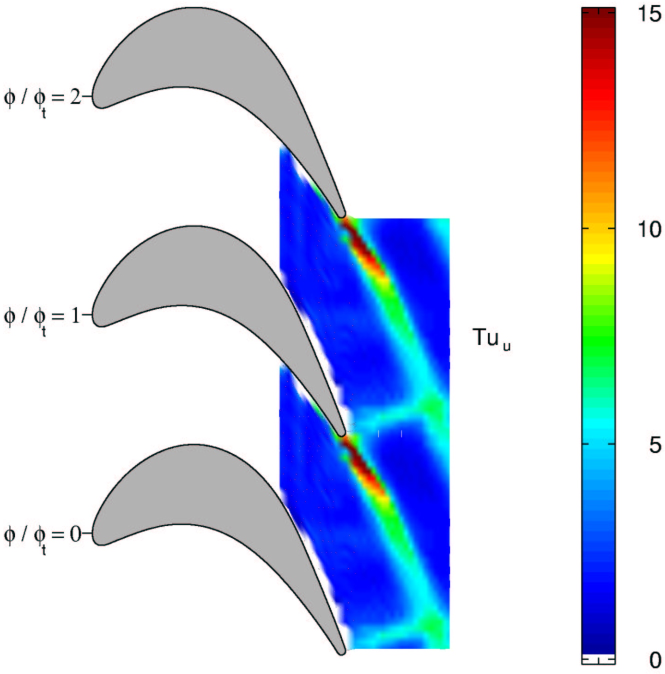

Figure 5: Streamwise turbulence intensity (in %) from L2F measurements in the midsection of a turbine rotor

The experimental uncertainty of the Laser measurements has been analysed and absolute error bars (on a 95 % confidence level) for the present measurements have been determined: The error bar for the Mach number was 0.003 outside the wakes and boundary layers and 0.01 inside. The error bar for the angle was 0.2° outside the wake and 0.5° inside. The error in the turbulence level was not so easy to determine. From the statistical analysis the absolute error bar was 0.3 % outside the wake and 0.6 % inside, but this did not take into account that lower frequency oscillations of the tunnel flow produce a higher measured turbulence intensity than really exists. In a comparison with a hot wire measurement in front of a cascade (the Mach number was there below 0.2), where certain precautions were taken (e.g. removing the particle seeding tube from the settling chamber), a good correspondence could be achieved: the hot wire gave a turbulence level of 0.7 %, the L2F 0.8 %. The uncertainty of the Reynolds shear stress is estimated to be less than $0.1 \cdot Tu_u \cdot Tu_v$.

An annular cascade of nozzle guide vanes with internal cooling and coolant ejection at the trailing edge was investigated in the transonic flow regime. The development of coolant concentration downstream of the guide vanes could be investigated together with the velocity field by seeding either main stream or coolant flow [6]. This was enabled by two features of the measurement equipment: First the seeding generator produces seeding particles at a rather constant rate. Secondly, the seeding particles consist of very small oil particles, which are able to follow the flow satisfactorily. When these conditions are fulfilled the measurement of the flow rate of oil particles downstream of the cascade is comparable to the measurement of the coolant concentration. To that purpose the application of only a part of the available L2F apparatus is required. One laser beam and one focus point suffice and, as no rotation of the focus points is required, a fast measurement procedure is possible. Figure 6 shows the progress of the downstream mixing for a ratio c_m = 2% of the mass flow ejected through the slot to the cascade mass flow. This figure was deduced from a dense grid of meassurement points.

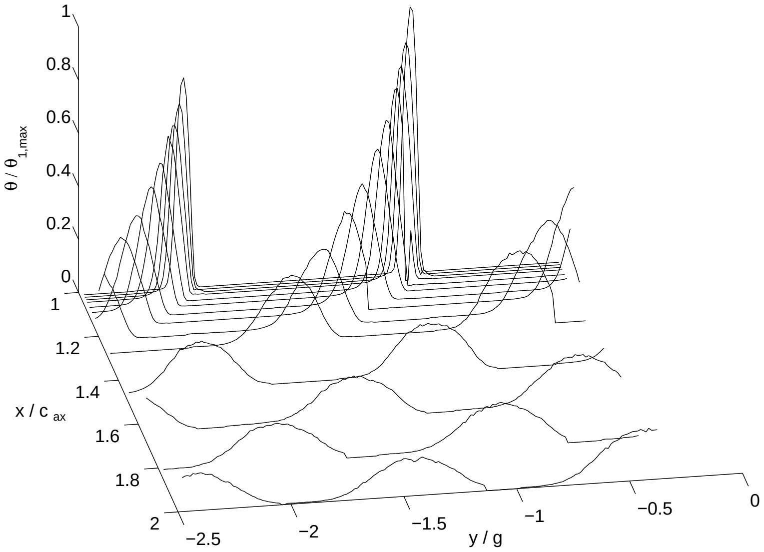

Figure 6: Coolant concentration measurement downstream of a turbine guide vane at Mach number $Ma_{2;\mathrm{is}} = 1.05$ with ejection rate c_m = 2%

5. Conclusion

The Laser-Two-Focus Technique (L2F) can be routinely applied to acquire flow field information for turbomachine flows. One of its main advantages is a good acces to narrow blade channels. The storage of the fully two-dimensional velocity distribution instead of only the two marginal distributions of transit time and angle led to several improvements, of which the most important is that Reynolds shear stress can be obtained. Investigations of rotor flow fields have been successfully performed without any problems and a few results have been presented.

Appendix: Evaluation of L2F-measurements

A statistical evaluation procedure is necessary to extract the desired mean flow values from the stored transit time distributions at the used angle settings.

A.1 Nomenclature and definitions

d	L2F-focus diameter	s	L2F-focus distance
α	angle	t	transit time
n	number of events	c	magnitude of velocity
u	streamwise velocity	v	transverse velocity
$\bar{u}, \bar{v}$	mean velocities	$u' = u - \bar{u}$, $v' = v - \bar{v}$	velocity fluctuations

$$c_\mathrm{j} = \frac{s}{t_\mathrm{j}}\left[1 + \left(\frac{t_{\mathrm{j}+1} - t_\mathrm{j}}{2t_\mathrm{j}}\right)^2\right]$$ mean magnitude of velocity in time interval j

$u_\mathrm{ij} = c_\mathrm{j} \cos(\alpha_\mathrm{i} - \bar{\alpha})$ streamwise velocity; $v_\mathrm{ij} = c_\mathrm{j} \sin(\alpha_\mathrm{i} - \bar{\alpha})$ transverse velocity

By the way, considering $\bar{\alpha}$ as a free parameter makes it possible to rotate the coordinate system of the evaluation.

The measured transit time distributions are characterized by numbers n_{ij}, i.e. at L2F-angle α_{i} and with transit time t_{j}, n_{ij} particles have traversed the start and stop focus (valid events) — n_{ij} is a frequency distribution.

Stray light from adjacent walls or particles which traverse only the start or only the stop focus may cause uncorrelated events which add a background noise to the frequency distribution. The background noise level n_{ri} has to be subtracted from the n_{ij}. The frequency distribution of flow angles results from summing up the $n_{\mathrm{ij}} - n_{\mathrm{ri}}$ at fixed angle:

$$n_{\mathrm{i}} = \sum_{\mathrm{j=j_1}}^{\mathrm{j_2}} (n_{\mathrm{ij}} - n_{\mathrm{ri}}) \qquad \text{flow angle distribution}$$

To account for the fact that the two focuses are more frequently crossed by fast particles than by slow ones (“statistical bias”) the frequency $n_{\mathrm{ij}} - n_{\mathrm{ri}}$ is weighted by $1/c_{\mathrm{j}}$, (see [1]).

$$f_{\mathrm{ij}} = \frac{n_{\mathrm{ij}} - n_{\mathrm{ri}}}{c_{\mathrm{j}}} \quad \text{weighted frequency;} \qquad \mathcal{N} = \sum_{\mathrm{i=i_1}}^{\mathrm{i_2}} \sum_{\mathrm{j=j_1}}^{\mathrm{j_2}} f_{\mathrm{ij}} \quad \text{sum of frequencies}$$

A.2 Statistical evaluation

By the statistical evaluation the mean values $\bar{u}, \bar{v}, \overline{u'^2}, \overline{v'^2}, \overline{u'v'}$ are calculated from the L2F transit time distributions.

$$\bar{u} = \frac{1}{\mathcal{N}} \sum_{\mathrm{i=i_1}}^{\mathrm{i_2}} \sum_{\mathrm{j=j_1}}^{\mathrm{j_2}} f_{\mathrm{ij}}\, u_{\mathrm{ij}} \qquad \bar{v} = \frac{1}{\mathcal{N}} \sum_{\mathrm{i=i_1}}^{\mathrm{i_2}} \sum_{\mathrm{j=j_1}}^{\mathrm{j_2}} f_{\mathrm{ij}}\, v_{\mathrm{ij}}$$

$$\overline{u'^2} = \frac{1}{\mathcal{N}} \sum_{\mathrm{i=i_1}}^{\mathrm{i_2}} \sum_{\mathrm{j=j_1}}^{\mathrm{j_2}} f_{\mathrm{ij}}\, (u_{\mathrm{ij}} - \bar{u})^2 \qquad \overline{v'^2} = \frac{1}{\mathcal{N}} \sum_{\mathrm{i=i_1}}^{\mathrm{i_2}} \sum_{\mathrm{j=j_1}}^{\mathrm{j_2}} f_{\mathrm{ij}}\, (v_{\mathrm{ij}} - \bar{v})^2$$

$$\overline{u'v'} = \frac{1}{\mathcal{N}} \sum_{\mathrm{i=i_1}}^{\mathrm{i_2}} \sum_{\mathrm{j=j_1}}^{\mathrm{j_2}} f_{\mathrm{ij}}\, (u_{\mathrm{ij}} - \bar{u})(v_{\mathrm{ij}} - \bar{v})$$

A.3 Further evaluation

When investigating rotor flows by L2F the velocity distributions are not measured at a fixed point but are values from an interval in circumferential direction, e.g. 1/32 of a blade gap in the investigations reported here. Already the variation of mean velocity in the interval produces an apparent turbulence level which has to be corrected at least at small turbulence intensities. The correction is done by subtracting $1/12(\Delta u)^2$ from $\overline{u'^2}$ resp. $\overline{v'^2}$, where Δu is the variation of mean velocity between neighbouring intervals (see [7]).

The turbulence intensities, reported here, are normalized by the local flow velocity $\bar{u}$. The transverse turbulence Tu_{v} is subject to a further correction, as the finite focus diameter d gives rise to an enlargement of the measured flow angle range and accordingly a larger transverse turbulence level results (see [4]). The correction is included in the equation (4). The influence of the finite focus diameter on the Reynolds' stress value R_{uv} is corrected by including the corrected value of Tu_{v} into the right side of equation (5).

$$Tu_{\mathrm{u}} = \frac{1}{\bar{u}} \sqrt{\overline{u'^2}} \qquad Tu_{\mathrm{v}} = \frac{1}{\bar{u}} \sqrt{\overline{v'^2} - \frac{1}{6}\left(\bar{u}\frac{d}{s}\right)^2} \tag{4}$$

$$R_{\mathrm{uv}} = -\frac{\overline{u'v'}}{\bar{u}^2} = Tu_{\mathrm{u}} \cdot Tu_{\mathrm{v}} \cdot r_{\mathrm{uv}} \qquad (r_{\mathrm{uv}} = \text{correlation}) \tag{5}$$

If rotor measurements have been performed the last step of the evaluation is the transformation from the absolute to the rotor fixed relative system. In this context it has to be remarked that computing the turbulence values in a new rotated coordinate system is only possible if the three mean fluctuating values $\overline{u'^2}, \overline{v'^2}, \overline{u'v'}$ are available in the original coordinate system.

A.4 Evaluation using a reduced number of angles

In order to achieve a reduction of measurement time, the L2F measurement procedure may be restricted to measurements of transit time distributions at fewer angles than necessary to scan the whole flow angle distribution (incomplete angle distributions). In such a case it is sufficient to have transit time distributions at three angles in the vicinity of the mean flow angle:

- The mean flow angle is set equal to that angle at which the angle distribution displays a maximum (the measurements at three angles make a parabolic interpolation possible).
- The mean magnitude of velocity and the streamwise turbulence may be received by evaluating that transit time distribution which is nearest to the maximum of the angle distribution.
- The transverse turbulence $\boldsymbol{Tu}_{\mathrm{V}}$ is computed from the height of the angle distribution according to equation (1), but Reynolds' shear stress is not available.

The procedure is described in more detail in [4]. In the case of roughly isotropic turbulence this "reduced" evaluation and the extensive one give very similar results, [8].

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